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The integrated scheduling for the multi-stage transshipment system considering AGVs and ETs

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***Abstract*—In sea-road intermodal container terminals, the integrated scheduling problem for the multi-stage transshipment system (ISP_MST_CT) is influenced by factors such as the number of containers, multi-stage interactions, and various types of equipment, making it challenging to construct the model. Additionally, assigning an appropriate number of AGVs to the transshipment tasks can significantly avoid resource waste at the terminals. This paper, for the first time, considers the ISP_MST_CT of quay cranes, AGVs, yard cranes, and external trucks, encompassing four operational stages. A mixed-integer programming model is formulated to simultaneously optimize the maximum completion time, total energy consumption of quay cranes and yard cranes, and total waiting time of AGVs. The nondominated sorting genetic algorithm II (NSGAII) algorithm is employed to solve this problem. The experiment results validate that NSGAII is capable of efficiently solving ISP_MST_CT of different scales and obtaining superior solutions within a short time. Furthermore, a series of experiments with 20 containers demonstrates that 8 AGVs can keep the balance among the three optimization objectives, while reducing the waste of AGVs and providing valuable insights to terminal managers.**

Keywords—sea-road container terminal, integrated scheduling, multi-stage, marginal benefits value of AGV, NSGAII

I. INTRODUCTION

Data from the United Nations Conference on Trade and Development (UNCTAD) [1] indicates that global container throughput has been steadily increasing, and the container terminals will face tremendous pressure due to the surge in container transportation volume in the future.

To better address the challenges of container terminal transshipment operations for sea-road intermodal transport, and overcome the impacts of multi-stage interactions in transshipment systems, it is urge to address the integrated scheduling for multi-stage transshipment system considering AGVs and external trucks (ETs).

Studies by Lau et al. (2008) [2], Chen et al. (2013) [3], Lu et al.(2014) [4] have considered the integrated scheduling of quay cranes (QC), automated guided vehicles (AGV), and yard cranes (YC). Various heuristic algorithms have been developed to solve these integrated problems. Luo et al. (2016) [5] addressed the integrated scheduling problem between import container storage allocation, AGV and YC scheduling, and proposed a genetic algorithm (GA) to solve the problem. Ji et al. (2020) [6] considered the integrated scheduling of QC, AGV, automated stacking cranes, and designed genetic algorithms based on conflict resolution strategies to solve the problem. Xu et al. (2021) [7] addressed the integrated scheduling problem of double trolley QC, AGV, and double cantilevered rail-mounted cranes, and proposed a reinforcement learning to solve the model. Liu et al. (2016) [9] studied the joint optimization of tactical berth allocation and tactical yard allocation in container terminals to address import, export, and transshipment tasks. In [10] (2022), the QC no-idle integrated container scheduling problem was solved.

In summary, there is still a lack of research on integrated scheduling problem involving QC, YC, AGV, and ET for sea-road container terminals. This paper proposes an integrated scheduling problem for the multi-stage transshipment system at the container terminals, referred to as ISP_MST_CT for the first time.

The mathematical model of ISP_MST_CT is constructed that simultaneously optimizes the maximum completion time, total energy consumption of QCs and YCs, and total waiting time of AGVs. Additionally, this paper considers the limited number of AGVs at the terminal, the effective marginal benefit value of AGVs is calculated to maximize resource utilization and reduce resource waste.

II. PROBLEM DESCRIPTION

The transshipment at the sea-road Intermodal Container Terminal generally include two processes: loading and unloading of vessels. The loading process is the opposite of the unloading process. Taking container unloading as an example, the transshipment operation process in sea-road intermodal container terminal is described as follows, shown as Figure 1.

It is assuming that there are H containers that need to be transferred from the vessel to the terminal yard, then from yard to external trucks (ETs). The operation stages are represented by O_1 for QC operation, O_2 for AGV transportation, O_3 for YC operation, and O_4 for ET transportation. As shown in Figure 1, each container will go through the four stages $O_1 \rightarrow O_2 \rightarrow O_3 \rightarrow O_4$ sequentially, and each operation stage is executed only once. The equipment used in each stage are homogeneous, while the equipment in different stages are heterogeneous, so we will introduce a hybrid flow shop scheduling problem model to describe the scenario and we refer it as the ISP_MST_CT.

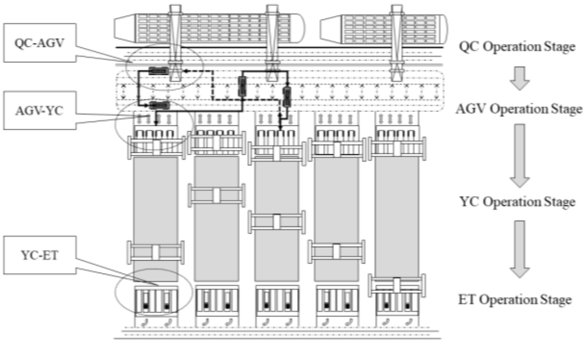

Fig. 1. The four operation stages of transshipment in sea-road intermodal container terminal.

The four stages of ISP_MST_CT are described as follows:

(a) The QC unloads the container onto the AGV before proceeding to the next container operation task. Otherwise, QC need to wait for AGV. Based on the current operation status of each QC, appropriate QCs are assigned to the H containers.

(b) The QC loads the container onto the waiting AGV, which transports the container to the yard that meets the storage requirements. If there is no available YC for O_2, the AGV with the loaded container waits in the yard until a YC, which has completed the previous task, becomes available. The AGV releases the container and completes the current task. If there is no subsequent transshipment task, the AGV returns to the AGV pool and waits. If there is a next transshipment task, the AGV returns to the berth area for loading the container. Based on the current operation status of each AGV, suitable AGVs are assigned to the containers.

(c) The YCs operate on the loaded AGVs that arrive at the yard. They can only proceed to the next container operation task after unloading the current container. Otherwise, they wait. Based on the current operation status of each YC, suitable YCs are assigned to the containers.

(d) The YCs will transfer the corresponding container to the waiting ETs. Each ET is responsible for the road transportation of an independent container.

The ISP_MST_CT aims to optimize the maximum completion time of container loading and unloading, as well as the total energy consumption of QC and YCs, and the total waiting time of AGVs. The following sub-problems need to be addressed: (1) the containers scheduling, (2) assigning container transshipment tasks to each AGV, (3) assigning container transshipment tasks to each QC at the berth, (4) assigning container transshipment tasks to YCs at the yard. It should be noted that the ET for each container has already been assigned. Therefore, there is no need to allocate additional container tasks to the ETs.

The model makes the following assumptions:

- All equipment is available at time zero.
- Each AGV has consistent operational capabilities, and all AGVs are shared among QC and YCs.
- Collisions of equipment are not considered.
- AGVs travel in a one-way direction within the container terminal, forming a closed loop between the berth and the yard.
- Each yard(berth) has multiple YCs(QCs), with consistent capabilities for large vehicle movement and small vehicle operations.
- There are no container storage buffers at the berth or the yard.
- During operations, QC, AGVs, and YCs operate at a constant speed with given operation speeds and power.
- The time windows requirement for ETs to pick up containers is not considered.

III. MATHEMATICAL MODEL

A. Symbol Definitions

h: Index of container

j: Index of AGV

q: Index of QC

r: Index of YC

e: Index of ET

B. Parameter Definitions

O_i: The ith operation process in the unloading process of containers, where i = 1, 2, 3, 4.

$O_{i,h}$: The ith operation for unloading container h, where i = 1, 2, 3, 4.

H: Total number of containers to be unloaded.

Ω: Set of containers to be unloaded, where $h \in \Omega$.

Q: Total number of QC at the terminal.

Ω_q: Set of container tasks assigned to QC q, with a total number of $|\Omega_q|$.

J: Total number of AGVs at the terminal, where $j \in \{1,2,\dots,J\}$.

Ω_j: Set of container tasks assigned to AGV j, with a total number of $|\Omega_j|$.

R: Total number of YCs at the terminal.

Ω_r: Set of container tasks assigned to YC r, with a total number of $|\Omega_r|$.

E: Total number of ETs at the terminal.

$p_{1,h}^{q}$: The process time of QC q to complete the operation for container h.

$p_{3,h}^{r}$: The process time of YC r to complete the operation for container h.

$p_{2,h}^{j}$: The process time of AGV j to transport container h from the berth to the yard.

p_{2}^{j}: The process time of empty AGV j to return from the yard to the berth.

$p_{4,h}^{e}$: The process time of ET *e* to complete the operation for container *h*.

C. Coefficients

θ_{q0}: Energy consumption coefficient of QC *q* in the idle state.

θ_{q1}: Energy consumption coefficient of QC *q* in the handling operational state.

θ_{r0}: Energy consumption coefficient of YC *r* in the idle state.

θ_{r1}: Energy consumption coefficient of YC *r* in the handling operational state.

D. Variables

$$x_{h,q} = \begin{cases} 1, O_1 \text{ of container } h \text{ is completed by QC } q \\ 0, \text{Otherwise} \end{cases}$$

$$y_{h,j} = \begin{cases} 1, O_2 \text{ of container } h \text{ is completed by AGV } j \\ 0, \text{Otherwise} \end{cases}$$

$$z_{h,r} = \begin{cases} 1, O_3 \text{ of container } h \text{ is completed by YC } r \\ 0, \text{Otherwise} \end{cases}$$

$$\beta_{h,h'}^{q} = \begin{cases} 1, h' \text{ is the immediately previous of } h \text{ on QC } q \\ 0, \text{Otherwise} \end{cases}$$

$$\mu_{h,h'}^{j} = \begin{cases} 1, h' \text{ is the immediately previous of } h \text{ on AGV } j \\ 0, \text{Otherwise} \end{cases}$$

$$\sigma_{h,h'}^{r} = \begin{cases} 1, h' \text{ is the immediately previous of } h \text{ on YC } r \\ 0, \text{Otherwise} \end{cases}$$

$S_{1,h}^{q}$: Start time of QC *q* for operation on container *h*.

$C_{1,h}^{q}$: End time of QC *q* for completing $O_{1,h}$.

$S_{2,h}^{j}$: Start time of AGV *j* for operation on container *h*.

$C_{2,h}^{j}$: End time of AGV *j* for completing $O_{2,h}$.

$S_{3,h}^{r}$: Start time of YC *r* for operation on container *h*.

$C_{3,h}^{r}$: End time of YC *r* for completing $O_{3,h}$.

$S_{4,h}^{e}$: Start time of ET *e* for operation on container *h*.

$C_{4,h}^{e}$: End time of ET *e* for completing $O_{4,h}$.

C_{1}^{q}: End time of Ω_q for QC *q*.

C_{2}^{j}: End time of Ω_j for AGV *j*.

C_{3}^{r}: End time of Ω_r for YC *r*.

C_{4}^{e}: End time of *h* for ET *e*.

$AR_{h,j}$: Arrived time when AGV *j* transports container *h* to the yard.

$AT_{h,j}$: Total waiting time of AGV *j* with container *h* in the yard.

$RT_{h,j}$: Released time when AGV *j* releases container *h* in the yard.

C_{max}: Maximum completion time among all containers.

EC : Total energy consumption of QCs and YCs for completing all containers.

WT: Total waiting time of AGVs for completing all containers

E. Objective Function

$$\min(C_{max}, EC, WT) \tag{1}$$

$$C_{max} = \max\{C_4^e | e \in \{1,2,\dots,E\}\} \tag{2}$$

$$EC = ECQ + ECR \tag{3}$$

$$ECQ = \sum_{q=1}^{Q}\sum_{h}^{\Omega_q}(\theta_{q1}\cdot x_{h,q}\cdot p_{1,h}^{q}) + \sum_{q=1}^{Q}\theta_{q0}\cdot x_{h,q}\cdot\left(C_1^q - \sum_{h}^{\Omega_q}p_{1,h}^{q}\right) \tag{4}$$

$$ECR = \sum_{r=1}^{R}\sum_{h}^{\Omega_r}(\theta_{r1}\cdot z_{h,r}\cdot p_{3,h}^{r}) + \sum_{r=1}^{R}(\theta_{r0}\cdot z_{h,r}\cdot(C_3^r - \sum_{h}^{\Omega_r}p_{3,h}^{r})) \tag{5}$$

$$WT = \sum_{h=1}^{\Omega_j}\sum_{j=1}^{J}AT_{h,j} \tag{6}$$

Equation (1) represents the objective function, which minimizes the maximum completion time (C_{max}), energy consumption (EC), and waiting time (WT). Equation (2) calculates the maximum completion time of the last task in Ω. Equation (3) decomposes the total energy consumption into ECQ and ECR, representing the energy consumption of QC and YC, respectively. Equation (4) calculates the QC handling operation energy consumption and the QC idle state energy consumption of Ω. Equation (5) calculates the YC handling operation energy consumption and the YC idle state energy consumption of Ω. Equation (6) calculates the total waiting time of AGVs.

F. Constraints

$$\sum_{q=1}^{Q}|\Omega_q| = H,\quad q \in \{1,2,\dots,Q\} \tag{8}$$

$$\sum_{j=1}^{J}|\Omega_j| = H,\quad j \in \{1,2,\dots,J\} \tag{9}$$

$$\sum_{r=1}^{R}|\Omega_r| = H,\quad r \in \{1,2,\dots,\mathrm{R}\} \tag{10}$$

Equation (8) ensures that the sum of assigned containers for QCs is equal to the total number of containers in the task set. Equation (9) ensures that the sum of assigned containers for AGVs is equal to the total number of containers in the task set. Equation (10) ensures that the sum of assigned containers for YCs is equal to the total number of containers in the task set.

$$C_1^q \geq \sum_{h}^{\Omega_q}x_{h,q}p_{1,h}^{q} \tag{11}$$

$$\sum_{q=1}^{Q}x_{h,q} = 1, \forall h \in \Omega \tag{12}$$

$$C_{1,h}^{q} \geq C_{1,h'}^{q}\beta_{h,h'}^{q} + \sum_{h=1}^{|\Omega_q|}x_{h,q}p_{1,h}^{q} \tag{13}$$

$$S_{1,h}^{q} = min\left\{C_{1,h'}^{q}\beta_{h,h'}^{q}\right\}, q \in \{1,2,\dots,Q\} \tag{14}$$

$$\sum_{h=1}^{H}\beta_{h,h'}^{q} = 1 \tag{15}$$

Where *h'* is the immediate predecessor of *h* on *q*. The start time of the first container on each QC is 0, represented by $S_{1,1}^{q}$=0. Equation (11) imposes a time constraint on each QC operation. Equation (12) ensures that any container in Ω is only operated once by one QC in the QC stage. Equation (13) requires that QC *q* can start the next container's operation only after completing the previous container's operation. Equation (14) assigns the next container to the QC that finishes the previous container's operation first. Equation (15) ensures that a container has only one immediately previous container on each QC.

$$S_{2,h}^{j} \geq \max\{C_{2,h'}^{j}\mu_{h,h'}^{j}, C_{1,h}^{q}\} \tag{16}$$

$$\begin{cases} AR_{h,j} = S_{2,h}^{j} + p_{2,h}^{j} \\ RT_{h,j} = \sum_{h}^{\Omega_j}y_{h,j}(p_{2,h}^{j} + AT_{h,j} + AR_{h,j}) \end{cases} \tag{17}$$

$$\sum_{j=1}^{J} y_{h,j} = 1, \forall h \in \Omega \quad (18)$$

$$C_{2,h}^{j} \geq p_2^{j} + RT_{h',j}\mu_{h,h'}^{j} \quad (19)$$

$$S_{3,h}^{r} \geq \max\{C_{3,h'}^{r}\sigma_{h,h'}^{r}, RT_{h,j}\} \quad (20)$$

$$\sum_{h=1}^{H} \mu_{h,h'}^{j} = 1 \quad (21)$$

$$\sum_{h=1}^{H} \sigma_{h,h'}^{r} = 1 \quad (22)$$

Where h' is the immediate predecessor of h on j. Equation (16) requires that the container must undergo QC operations before it can be transported by a AGV. Equation (17) represents process O_2, which includes three parts: transporting loaded containers from the berth to the yard using a AGV, waiting at the yard for YCs to release the containers, and returning empty from the yard to the berth. Equation (18) stipulates that any container can only be handled once by a AGV during the AGV transportation stage and cannot be handled repeatedly. Equation (19) requires AGV j to return to the berth and accept the next container transportation task only after completing the previous container transfer task. Equation (20) specifies that the start time of YC operations must occur after completing the previous task and when there is a AGV tasked with transporting a loaded container waiting for operations. Equation (21)-(22) ensure that a container has only one previous container on each AGV and YC.

$$\sum_{r=1}^{R} z_{h,r} = 1, \forall h \in \Omega \quad (23)$$

$$C_{3,h}^{r} \geq C_{3,h}^{r} + \sum_{h=1}^{Hr} z_{h,r} p_{3,h}^{r} \quad (24)$$

Where h' is the immediate predecessor of h on r. Equation (23) requires that any container is only operated once by one YC. Equation (24) requires that YC r can start the next container's operation only after completing the previous container's operation.

$$S_{4,h}^{e} = C_{3,h}^{r} \quad (25)$$

$$C_{4,h}^{e} = S_{4,h}^{e} + p_{4,h}^{e} \quad (26)$$

Equations (25) and (26) indicate that each ET can only transport a specified container.

IV. NSGAII FOR ISP_MST_CT

In this section, we adopt the NSGAII for ISP_MST_CT. The NSGAII includes four phases: The solution representation, crossover phase, mutation phase, and discretization phase.

A. Solution Representation

A solution $\vec{X} = [\vec{H}, \vec{Q}, \vec{G}, \vec{R}, \vec{E}]$ that consists of five vectors, which concludes container and four equipment, namely: 1) container transshipment sequence ($\vec{H}$); 2) QC sequence ($\vec{Q}$); 3) AGV sequence ($\vec{G}$); 4) YC sequence ($\vec{R}$); 5) ET sequence ($\vec{E}$).

(1) Randomly generate a series of integer numbers composed of H dimensions.

(2) For each container, each container will be equipped with one QC, AGV, YC using the typical priority dispatching rule of early complete time (ECT) [8].

(3) Each container is ultimately transported by a unique and independent ET.

Finally, a feasible solution $\vec{X} = [\vec{H}, \vec{Q}, \vec{G}, \vec{R}, \vec{E}]$ is always obtained as shown in equation (27)

The steps are repeated N and then an initial population P with N solutions is obtained.

$$\vec{X} = [\vec{H}, \vec{Q}, \vec{G}, \vec{R}, \vec{E}] = \begin{bmatrix} \vec{H}(1), \vec{H}(2), \dots, \vec{H}(h), \dots, \vec{H}(H) \\ \vec{Q}(1), \vec{Q}(2), \dots, \vec{Q}(h), \dots, \vec{Q}(H) \\ \vec{G}(1), \vec{G}(2), \dots, \vec{G}(h), \dots, \vec{G}(H) \\ \vec{R}(1), \vec{R}(2), \dots, \vec{R}(h), \dots, \vec{R}(H) \\ \vec{E}(1), \vec{E}(2), \dots, \vec{E}(h), \dots, \vec{E}(H) \end{bmatrix} \quad (27)$$

B. Crossover Phase

The crossover operation is executed for container sequence $\overrightarrow{H1}$=[$\overrightarrow{H1}(1)$, $\overrightarrow{H1}(2)$,…, $\overrightarrow{H1}(h)$,…, $\overrightarrow{H1}(H)$] and $\overrightarrow{H2}$=[$\overrightarrow{H2}(1)$, $\overrightarrow{H2}(2)$,…, $\overrightarrow{H2}(h)$,…, $\overrightarrow{H2}(H)$] by using equation s. (28)~(30).

Let $u(h)$ is a continuous value, generated randomly in the range of [0,1], co is a constant value, $bq(h)$ is the crossover value, $\overrightarrow{ch1}(h)$ and $\overrightarrow{ch2}(h)$ are the intermediate continuous sequences of $\overrightarrow{cH1}$ and $\overrightarrow{cH2}$. The updating of $\vec{H}$ in each individual are affected by $u(h)$, $bq(h)$, and co.

$$bq(h) = \begin{cases} (2 * u(h))^{\frac{1}{co+1}}, u(h) \leq 0.5 \\ (2 * (1 - u(h)))^{\frac{-1}{co+1}}, u(h) > 0.5 \end{cases} \quad (28)$$

$$\overrightarrow{ch1}(h) = 0.5 * \left(\left(1 + bq(h)\right) * \overrightarrow{H1}(h) + \left(\left(1 - bq(h)\right)\right) * \overrightarrow{H2}(h)\right) \quad (29)$$

$$\overrightarrow{ch2}(h) = 0.5 * \left(\left(1 - bq(h)\right) * \overrightarrow{H1}(h) + \left(\left(1 + bq(h)\right)\right) * \overrightarrow{H2}(h)\right) \quad (30)$$

C. Mutation phase

Let $l(h)$ is a continuous value, generated randomly in the range of [0,1], mu is a constant value, $bd(h)$ is the mutation value. The updating of $\vec{H}$ in each individual are affected by $l(h)$, $bd(h)$, and mu.

$$bd(h) = \begin{cases} (2 * l(h))^{\frac{1}{mu+1}} - 1, l(h) \leq 0.5 \\ 1 - (2 * (1 - l(h)))^{\frac{1}{mu+1}}, l(h) > 0.5 \end{cases} \quad (31)$$

$$\overrightarrow{ch1}(h) = \overrightarrow{H1}(h) + bd(h) \quad (32)$$

$$\overrightarrow{ch2}(h) = \overrightarrow{H2}(h) + bd(h) \quad (33)$$

D. Discretization phase

The equation (34) is used to translated the continuous sequence $\overrightarrow{ch}$ into discrete sequence. First, sort the $\overrightarrow{ch}$ in descending order to obtain the intermediate sequences $\vec{\varphi} = [\vec{\varphi}(1), \dots, \vec{\varphi}(j), \dots, \vec{\varphi}(H)]$. Second, use equation (34) to construct the discrete $\overrightarrow{cH}$ as the final container sequence of child individual.

$$\overrightarrow{cH}(\vec{\varphi}(d)) = d \quad (34)$$

I. EXPERIMENTS

This section is devoted to evaluating the performance of proposed algorithm NSGAII for ISP_MST_CT. A set of instances under differential scales is generated randomly.

Part A experiments include 16 instances of $H\_Q\_J\_R$: 20_2_6_3, 40_3_9_4, 80_3_9_6, 150_6_18_8, 20_2_8_3, 40_3_12_4, 80_3_12_6, 150_6_24_8, 20_2_10_3, 40_3_15_4, 80_3_15_6, 150_6_30_8, 20_2_12_3, 40_3_18_4, 80_3_18_6, 150_6_36_8. Part B experiments include 12 instances of $H\_Q\_J\_R$ which are based on the scale of 20_2_3 (H_Q_R). the J is in the range of [6,17].

All operation data are collected from a busy container terminal in China. In our instances, the data are generated within the actual investigated range. The $p^q_{1,h}$ is randomly generated from a uniform distribution[100,140]s, $p^r_{3,h}$ is randomly generated from a uniform distribution $U[145,175]$s, the $p^j_{2,h}$ is randomly generated from $U[300,333]$s, the p^j_2 is randomly generated from $U[110,140]$s, the $p^e_{4,h}$ is generated from $U[30,50]$s. The θ_{q0} is generated from $U[100, 150]KVA$, θ_{q1} is generated from $U[2000, 2500]KVA$, θ_{r0} is generated from $U[50, 100]$ KVA, θ_{r0} is generated from $U[200, 210]KVA$. In our tests, NSGAII use the parameters: the population size $popsize = 20$, the constant values $co = 20$ and $mu = 20$, Each instance is independently run for 20 times at the same runtime. The final result shown in Tables for each instance is the minimum C_{max} individual in the Pareto front set. The solution is obtained by mixing 20 sets obtained by the 20 independent running. The termination criterion is set to 200. All algorithms used in the comparisons are coded in Matlab R2018a and executed on a computer with Intel(R) Core(TM) i7-8655U 1.90GHz with 8GB of RAM.

A. Statistical Results

It can be seen from Table I that in different-sized instances, INSGA-II can effectively solve the three objectives of ISP_MST_CT and obtain the excellent solutions. With a significant increase in the number of QC and YC, the *EC* value also increases significantly, confirming that QC and YC are the main energy-consuming equipment in container terminals. However, the association between *WT* and *H* is still not clear. We speculate that the *WT* and the current configurations of QC, AGV, and YC may be related. Therefore, the Part *B* experiments analyze the marginal effects of the number of AGVs.

TABLE I. STATISTICAL RESULTS OF NSGAII FOR ISP_MST_CT WITH 200 GENERATIONS IN DIFFERENT SCALES

Num	Ins.	Cmax/s	EC/kWh	WT/s
1	20_2_6_3	1956	2286	74
2	40_3_9_4	2454	4415	120
3	80_3_9_6	4360	8745	20
4	150_6_18_8	4145	16242	539
5	20_2_8_3	1737	2244	26
6	40_3_12_4	2134	4391	881
7	80_3_12_6	3601	8611	26
8	150_6_24_8	3508	16186	2810
9	20_2_10_3	1712	2245	345
10	40_3_15_4	2139	4399	1704
11	80_3_15_6	3556	8615	15
12	150_6_30_8	3461	16009	7724
13	20_2_12_3	1727	2251	237
14	40_3_18_4	2111	4354	1652
15	80_3_18_6	3556	8640	16
16	150_6_36_8	3482	16203	6431

B. Analysis of the marginal benefits value of AGV

This section of experiments focuses on the 20_2_3 scale, with 6 to 17 AGVs participating in container transportation for each instance. The results are shown in Table II.

It can be seen from Table II that as the number of AGVs increases, the obtained solutions do not continuously optimize. There exists an effective marginal benefits value for the number of AGVs. When the value is exceeded some constant, increasing the number of AGVs will not bring further positive benefits but rather result in resource waste.

TABLE II. STATISTICAL RESULTS OF NSGAII FOR ISP_MST_CT WITH DIFFERENT AGVS ON THE SCALE OF 20_2_3.

Num	Ins.	Cmax/s	EC/kWh	WT/s
17	20_2_6_3	1956	2275	96
18	20_2_7_3	1791	2265	94
19	20_2_8_3	1737	2236	138
20	20_2_9_3	1727	2254	128
21	20_2_10_3	1712	2245	345
22	20_2_11_3	1716	2229	273
23	20_2_12_3	1716	2228	192
24	20_2_13_3	1712	2231	275
25	20_2_14_3	1705	2230	131
26	20_2_15_3	1695	2227	321
27	20_2_16_3	1727	2269	215
28	20_2_17_3	1696	2217	219

To clearly demonstrate the relationships of the number of AGVs, the C_{max}, the *EC*, and the *WT*, the 12 solutions in Table 2 are presented as Figures 2, the three mappings are shown in Figures 3~5, the curve of number of AGVs and the Cmax on the scale of 20_2_3 is charted in Figure 6.

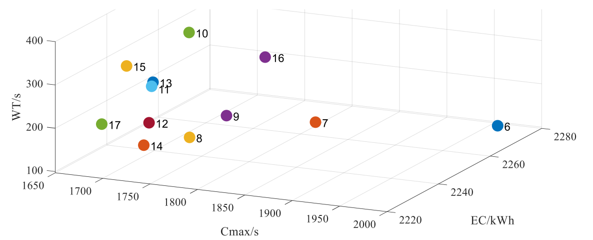

Fig. 2. The solutions of the scale of 20_2_3 with different AGVs

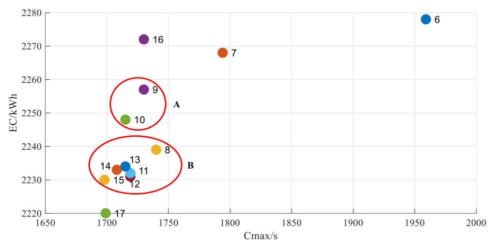

Fig. 3. The relationship between the Cmax and the EC on the scale of 20_2_3 with different AGVs.

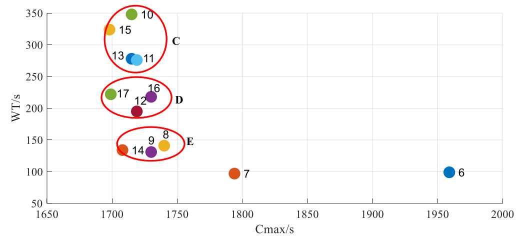

Fig. 4. The relationship between the Cmax and the WT on the scale of 20_2_3 with different AGVs.

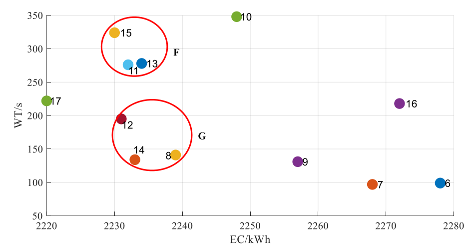

Fig. 5. The relationship between the EC and the WT on the scale of 20_2_3 with different AGVs.

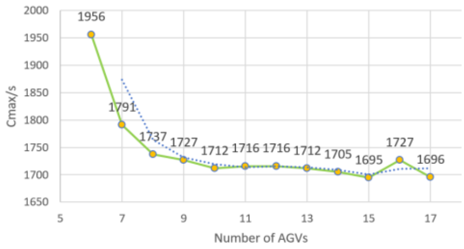

Fig. 6. The curve of the number of AGVs and the Cmax on the scale of 20_2_3.

In figures 3 and 4, there are five distinct clusters, A~E, respectively. In figure 5, there are no obvious relationship between the *WT* and the *ET*. To saving equipment resources as possible, the lowest number can be chosen in each cluster. In A, 9 AGVs can be selected. In B, 8 AGVs can be selected. In C, 11 AGVs can be selected. In D, 12 AGVs can be selected. In E, 8 AGVs can be selected. In F, 11 AGVs can be selected. In G, 8 AGVs can be selected. Finally, 8 AGVs can be selected to ensure the balance of *EC*, *WT*, and the minimal C_{max}. Additionally, when number of AGVs more than 8, the value of C_{max} tends to stabilize, as shown in figure 6. Therefore, the 8 AGVs is selected for the scale of 20_2_3.

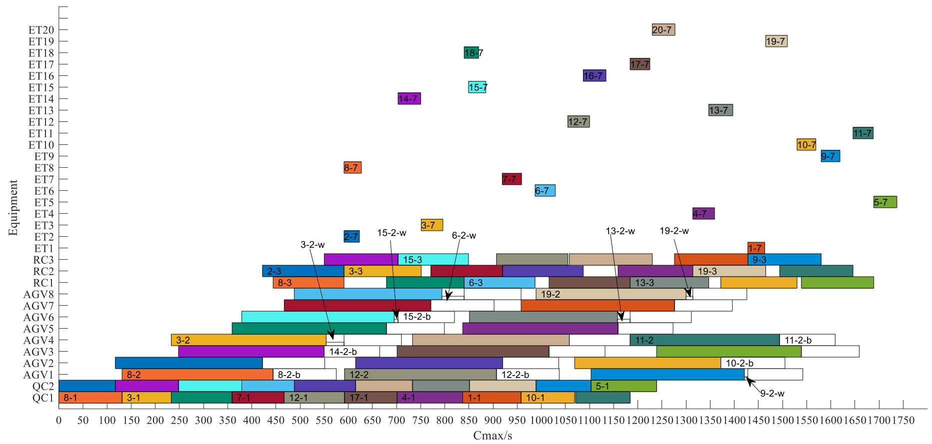

Fig. 7. Gantt chart of the scheduling scheme for 20_2_8_3.

In the following figure, a Gantt chart is provided for a scheduling scheme with 2 QC, 3 YCs, and 8 AGVs. The chart illustrates the order of container handling tasks for QC, the sequence of transportation tasks for AGVs, the waiting time for AGV loading, the order of tasks for YCs, and the completion time for ET.

II. CONCLUSION

This study addressed the integrated scheduling problem of the multi-stage transshipment system with QCs, AGVs, YCs, and ETs for the first time. A mixed-integer programming model is constructed, incorporating three objectives: C_{max}, *EC*, and *WT*. Experiment results demonstrate that the NSGAII is capable of effectively solving the integrated problem at different scales. Under the specific configuration combinations of containers, QCs and YCs, there exists an effective marginal benefit value for AGVs. When the number of AGVs exceeds the marginal benefit value, the scheduling scheme for transshipment no longer exhibits significant optimization. The 20_2_3 scale experiments indicate that the demands of the three objective values can be balanced while minimizing resource waste when the number of AGVs is set to 8.

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